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The Q^2-dependence of the generalised Gerasimov–Drell–Hearn integral for the proton

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Abstract

The dependence on Q^2 (the negative square of the 4-momentum of the exchanged virtual photon) of the generalised Gerasimov–Drell–Hearn integral for the proton has been measured in the range 1.2 GeV^2 $< Q^2 <$ 12 GeV^2 by scattering longitudinally polarised positrons on a longitudinally polarised hydrogen gas target. The contributions of the nucleon-resonance and deep inelastic regions to this integral have been evaluated separately. The latter has been found to dominate for $Q^2 > 3$ GeV^2, while both contributions are important at low Q^2. The total integral shows no significant deviation from a $1/Q^2$ behaviour in the measured Q^2 range, and thus no sign of large effects due to either nucleon-resonance excitations or nonleading twist.

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The Gerasimov–Drell–Hearn (GDH) sum rule [1] relates the anomalous contribution κ in the nucleon magnetic moment to an energy-weighted integral of the difference of the nucleon total spin-dependent photoabsorption cross sections:

$$\int_{\nu_0}^{\infty} \left[\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right] \frac{\mathrm{d}\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2, \tag{1}$$

where $\sigma_{1/2(3/2)}$ is the photoabsorption cross section for total helicity of the photon–nucleon system equal to 1/2 (3/2), ν is the photon energy in the target rest frame, ν_0 is the pion production threshold and M is the nucleon mass. For the proton ($\kappa_\mathrm{p} = +1.79$) the GDH sum rule prediction is -204 μb. The importance of this sum rule is due to the fact that it is based mostly on very general principles of causality, unitarity, crossing symmetry, and Lorentz and gauge invariance. It has never been directly tested, due to the need for a circularly polarised beam with a longitudinally polarised target, and a wide range of photon energies that has to be covered. There are available several predictions for the contribution of nucleon-resonance excitation to the GDH integral [2], derived from multipole analyses of data for unpolarised single-pion photoproduction, and a prediction for the contribution of high-energy multihadron production [3], based on a multiple-reggeon exchange analysis of deep inelastic asymmetries. The estimate from multipole analysis was confirmed by preliminary results from the GDH experiment at Mainz [4], which covered the photon-energy range from 200 MeV up to 800 MeV.

The GDH integral can be generalised to the case of absorption of polarised transverse virtual photons with squared four-momentum $-Q^2$ [5]:

$$I_{\mathrm{GDH}}(Q^2) \equiv \int_{\nu_0}^{\infty} \left[\sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)\right] \frac{\mathrm{d}\nu}{\nu} \tag{2}$$

$$= 16\pi^2\alpha \int_0^{x_0} \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{Q^2\sqrt{1+\gamma^2}}\,\mathrm{d}x \tag{3}$$

$$= \frac{8\pi^2\alpha}{M} \int_0^{x_0} \frac{A_1(x, Q^2) F_1(x, Q^2)}{K} \frac{\mathrm{d}x}{x}, \tag{4}$$

where g_1 and g_2 are the polarised structure functions of the nucleon, $\gamma^2 = Q^2/\nu^2 = (2Mx)^2/Q^2$, $x = Q^2/2M\nu$ and $x_0 = Q^2/2M\nu_0$. The quantity A_1 is the longitudinal asymmetry for virtual photoabsorption, while F_1 is the unpolarised structure function of the nucleon. The Gilman notation [6] for the virtual photon flux factor $K = \nu\sqrt{1+\gamma^2}$ has been used. It should be noted that elastic scattering occurring at $x = 1$ does not contribute to the generalised integral. Other generalisations of the GDH integral also have been considered [5]. They differ from the definition given in Eq. (2) by terms in the integral that are proportional to γ^2 and which therefore vanish in both the real-photon ($Q^2 = 0$) and the deep inelastic ($Q^2 \gg 1\ \mathrm{GeV}^2$ and $\gamma^2 \to 0$) limits. Since γ^2 is not small in the nucleon-resonance region and at moderate Q^2 (e.g. γ^2 is larger than unity for the $P_{33}(1232)$-resonance for $0.2\ \mathrm{GeV}^2 < Q^2 < 2\ \mathrm{GeV}^2$), these generalisations are equivalent for finite values of Q^2 only if the contributions of the nucleon-resonance excitations are small.

The generalisation of the GDH integral to nonzero photon virtuality Q^2 provides a way to study the transition from polarised lepton scattering from the nucleon, which is dominated by deep inelastic scattering (DIS) at large photon–nucleon centre-of-mass energy $W = \sqrt{M^2 + 2M\nu - Q^2}$, to the polarised real photon absorption on the nucleon, which is dominated by nucleon-resonance excitation at low W. In leading twist (e.g. for $Q^2 \to \infty$), Eq. (3) simplifies: the elastic contribution excluded from the integral is of higher twist, the factor $1/\sqrt{1+\gamma^2}$ is $1 + \mathcal{O}(1/Q^2)$, and in leading-twist approximation it is generally believed (though not formally proven) that the Burkhardt–Cottingham sum rule $\int_0^1 g_2(x, Q^2)\,\mathrm{d}x = 0$ holds. This leads to:

$$I_{\mathrm{GDH}}(Q^2)_{\gamma^2 \to 0} = \frac{16\pi^2\alpha}{Q^2}\Gamma_1, \tag{5}$$

where

$$\Gamma_1 \equiv \int_0^1 g_1(x)\,\mathrm{d}x$$

is predicted to have only the weak Q^2-dependence due to QCD evolution. As $Q^2 \to 0$, $I_{\mathrm{GDH}}(Q^2)$ must change sign in order to reach the negative value predicted by the GDH sum rule at $Q^2 = 0$.

Several phenomenological models have been proposed to describe the dependence of the generalised GDH integral on Q^2 [7–11]. Some of these models predict large effects from nucleon-resonance excitation [9,10] or from higher twist [7,11], even for Q^2 up to a few GeV^2. Other models based on chiral perturbation theory have been proposed but their application is limited to $Q^2 \ll 1\ \mathrm{GeV}^2$ [12].

The contribution of the region $W^2 \geqslant 3.24\ \mathrm{GeV}^2$ to the GDH integral defined in Eq. (2) was recently measured [13] for the proton and the neutron in the range $0.8\ \mathrm{GeV}^2 \leqslant Q^2 \leqslant 12\ \mathrm{GeV}^2$, showing that higher-twist effects do not appear to be significant in the measured region. This paper presents a measurement of the contribution of the resonance region to the GDH integral for the proton in a similar Q^2-range ($1.2\ \mathrm{GeV}^2 \leqslant Q^2 \leqslant 12\ \mathrm{GeV}^2$). In combination with the analysis at higher W^2, this provides the first experimental determination of essentially the complete GDH integral for the proton over a range of Q^2 values.

The measurement was performed in 1997 with a 27.56 GeV beam of longitudinally polarised positrons incident on a longitudinally polarised ^{1}H gas target internal to the HERA storage ring at DESY. The beam polarisation was measured continuously using Compton backscattering of circularly polarised laser light [14]. The average beam polarisation for the analysed data was 0.55.

The HERMES polarised target [15] consists of polarised atomic ^{1}H gas confined in a storage cell, which is a 40 cm long open-ended thin-walled elliptical tube located on the beam axis inside the HERA vacuum pipe. It is fed by an atomic-beam source of nuclear-polarised hydrogen based on Stern–Gerlach separation [16]. It provides an areal target density of about $7 \times 10^{13}\mathrm{atoms/cm}^2$. The nuclear polarisation of atoms and the atomic fraction are continuously measured with a Breit–Rabi polarimeter and a target gas analyser [17]. The average value of the target polarisation for the analysed data was 0.88 [18]. The fractional systematic uncertainties of the beam and target polarisations were 3.4% and 4.5%, respectively. The integrated luminosity for this data set was $70\ \mathrm{pb}^{-1}$.

Scattered positrons were detected by the HERMES forward spectrometer, which is described in detail elsewhere [19]. The kinematic requirements on the scattered positrons for the analysis in the nucleon-resonance region were: $1\ \mathrm{GeV}^2 < W^2 < 4.2\ \mathrm{GeV}^2$, $1.2\ \mathrm{GeV}^2 < Q^2 < 12\ \mathrm{GeV}^2$. After applying data quality criteria, about 0.13 million events were selected.

For all detected positrons the angular resolution was better than 0.6 mrad, the momentum resolution was better than 1.6% aside from bremsstrahlung tails and the Q^2-resolution was better than 2.2%. The limited W^2-resolution (about 840 MeV^2, or $\Delta W \simeq 240$ MeV) in the resonance region did not allow the contributions of the individual nucleon resonances to be distinguished. To evaluate the smearing corrections and the contaminations intruding into the resonance region from the elastic and deep inelastic regions, events were simulated using a Monte-Carlo code that includes elastic, deep inelastic and resonance contributions. The description of the resonance contribution was based on the model of Ref. [20]. The deep inelastic region was modelled using the parameterisation of Ref. [21] while the elastic form factors were taken from Ref. [22]. In Fig. 1 the distribution of events as a function of W^2 is presented in comparison with the simulation. It is apparent that the shape of the simulated distribution agrees well with that of the data. It was found that the relative contaminations from the elastic and DIS regions in the yield of the resonance region range from 10% to 2% and from 7% to 16% respectively, as Q^2 increases from 1.2 GeV^2 up to 12 GeV^2.

Data were divided into six bins in Q^2, but only one bin in W^2. In each Q^2-bin the average longitudinal asymmetry A_1 for virtual photoabsorption was calculated using the formula

$$A_1 = \frac{A_\parallel}{D} - \eta A_2, \tag{6}$$

where D and η are factors [13] that depend on kinematic variables. The quantity D depends also on $R = \sigma_{\mathrm{L}}/\sigma_{\mathrm{T}}$, the ratio of the absorption cross sections for longitudinal and transverse virtual photons. A_2 is

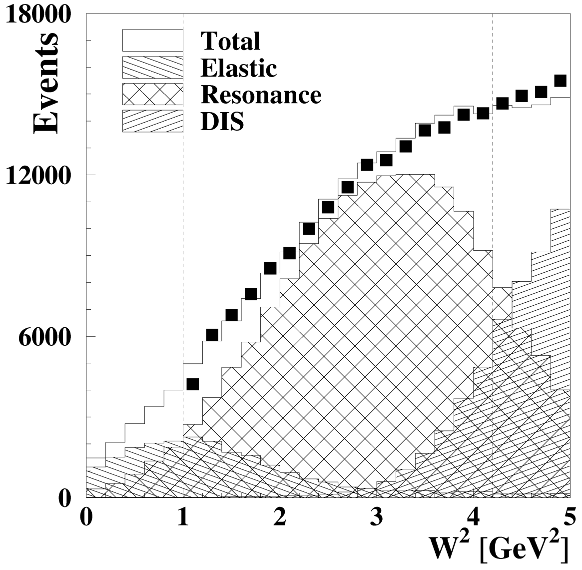

Fig. 1. Comparison of the event distribution for $W^2 > 1$ GeV^2 (squares) with the Monte-Carlo simulation (histogram). An overall normalisation factor was applied to the simulation to match the data. Also shown are the smeared distributions from the elastic, resonance and the deep inelastic regions. The vertical lines indicate the resonance region considered in the analysis.

related to longitudinal-transverse interference. The cross section asymmetry $A_\parallel$ is given by:

$$A_\parallel = \frac{N^{\rightleftarrows} L^{\rightrightarrows} - N^{\rightrightarrows} L^{\rightleftarrows}}{N^{\rightleftarrows} L_{\mathrm{P}}^{\rightrightarrows} + N^{\rightrightarrows} L_{\mathrm{P}}^{\rightleftarrows}}. \tag{7}$$

Here, $N^{\rightrightarrows}$ ($N^{\rightleftarrows}$) is the number of scattered positrons for target spin parallel (anti parallel) to the beam spin orientation. The deadtime-corrected luminosities for each target spin state are $L^{\rightrightarrows(\rightleftarrows)}$ and $L_{\mathrm{P}}^{\rightrightarrows(\rightleftarrows)}$, the latter being weighted by the product of beam and target polarisations. The cross-section asymmetry $A_\parallel^{\mathrm{res}}$ in the resonance region was corrected for contaminations originating from elastic and deep inelastic scattering, as discussed above. The asymmetry for the elastic contribution was taken from [22], while for the DIS region a parameterisation [23] based on world data has been used. Model dependent uncertainties due to these asymmetries and contributions from the Monte-Carlo simulation are negligible, as this correction is less than 5% for $Q^2 < 5$ GeV^2. Radiative corrections were calculated using the codes described in Ref. [24], and were found not to exceed 2% of the asymmetry $A_\parallel^{\mathrm{res}}$. The values for $A_1^{\mathrm{res}} + \eta A_2^{\mathrm{res}}$ for the measured range of Q^2 values are presented in Table 1. The asymmetry A_1 was evaluated using Eq. (6) under the assumption that $A_2 = 0.06$ [25] in the whole resonance region, and with an average depolarisation factor D weighted by the event distribution.

The contribution $I_{\mathrm{GDH}}^{\mathrm{res}}$ of the resonance region to the GDH integral was determined in each Q^2-bin from the asymmetry A_1, according to Eq. (4), in which the integration limits were determined by the 1 GeV$^2 < W^2 < 4.2$ GeV^2 range. The unpolarised structure function $F_1 = F_2(1+\gamma^2)/(2x(1+R))$ was calculated from a modification of the parameterisation of F_2 given in Ref. [20] that accounts for nucleon-resonance excitation assuming $R = \sigma_{\mathrm{L}}/\sigma_{\mathrm{T}}$ is constant and equal to 0.18 in the whole resonance region. It is worth noting that due to cancellation between the R-dependences of F_1 and D at low y, the final result is insensitive to the choice of R. In the integration

Table 1
Results for $A_1^{\mathrm{res}} + \eta A_2^{\mathrm{res}}$, the resonance part ($I_{\mathrm{GDH}}^{\mathrm{res}}$) to the GDH integral, and the total measured integral ($I_{\mathrm{GDH}}^{\mathrm{meas}}$), as well as the full GDH integral (I_{GDH}), including the unmeasured part. Errors represent the statistical uncertainty for $A_1^{\mathrm{res}} + \eta A_2^{\mathrm{res}}$ and the statistical and the systematic uncertainties of the integrals

$\langle Q^2 \rangle$ [GeV^2]	$A_1^{\mathrm{res}} + \eta A_2^{\mathrm{res}}$	$I_{\mathrm{GDH}}^{\mathrm{res}}$ [μb]	$I_{\mathrm{GDH}}^{\mathrm{meas}}$ [μb]	I_{GDH} [μb]
1.5	0.71 ± 0.16	$21.4 \pm 5.2 \pm 4.1$	$37.9 \pm 5.5 \pm 5.1$	$41.2 \pm 5.5 \pm 5.1$
2.1	0.77 ± 0.18	$10.3 \pm 2.5 \pm 2.0$	$24.3 \pm 2.8 \pm 2.9$	$27.8 \pm 2.8 \pm 2.9$
2.7	0.74 ± 0.22	$4.9 \pm 1.5 \pm 0.9$	$17.5 \pm 1.8 \pm 1.8$	$21.0 \pm 1.8 \pm 1.8$
3.5	0.79 ± 0.22	$2.4 \pm 0.7 \pm 0.4$	$13.0 \pm 1.0 \pm 1.2$	$16.5 \pm 1.0 \pm 1.2$
4.5	0.97 ± 0.29	$1.3 \pm 0.4 \pm 0.2$	$8.8 \pm 0.6 \pm 0.8$	$12.3 \pm 0.6 \pm 0.8$
6.6	0.55 ± 0.23	$0.08 \pm 0.03 \pm 0.01$	$5.3 \pm 0.3 \pm 0.5$	$8.6 \pm 0.3 \pm 0.5$

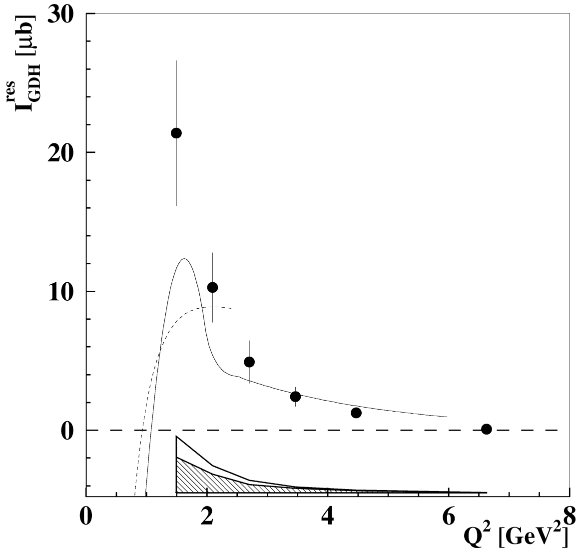

Fig. 2. The GDH integral as a function of Q^2 for the region $1.0\ \text{GeV}^2 < W^2 < 4.2\ \text{GeV}^2$. The error bars show the statistical uncertainties. The white and the hatched bands represent the systematic uncertainties with and without the A_2 uncertainty contribution. The dashed [9] and the solid [10] curves are predictions based on a Q^2-evolution of nucleon-resonance amplitudes.

the W^2 dependence of the integrand F_1/K within the individual bins was fully accounted for.

The results for I^{res}_{GDH} are presented in Fig. 2. The integral strongly decreases with Q^2 over the entire measured range. The magnitude of the systematic uncertainty is indicated by the band. The dominant contribution to the systematic uncertainty is due to the lack of knowledge of A_2. This contribution (up to 15%) was evaluated from the total error quoted for a measurement in the resonance region: $A_2 = 0.06 \pm 0.16$ [25]. This range is consistent with two other possible assumptions for A_2: $A_2 = 0$, or $A_2 = 0.53Mx/\sqrt{Q^2}$, which describes the behaviour in the deep inelastic region [18]. Other contributions are uncertainties from the beam and target polarisations (5.3%), from the spectrometer geometry (2.5%), from the combined smearing and radiative effects (up to 10%) and from the knowledge of F_2 (2%). The smearing contribution to the systematic uncertainty was evaluated by comparing simulated results from two very different assumptions for A_1: a power law ($A_1 = x^{0.727}$) that smoothly extends the DIS behaviour for the asymmetry into the resonance region [23], and a step function ($A_1 = -0.5$ for $W^2 < 1.8\ \text{GeV}^2$ and $A_1 = +1.0$ for $1.8\ \text{GeV}^2 < W^2 < 4.2\ \text{GeV}^2$) that is suggested by the hypothesis of the possible dominance of the P_{33}-resonance at low W^2 and of the S_{11}-resonance at higher W^2.

The results for I^{res}_{GDH} are compared in Fig. 2 with two predictions for the contribution of nucleon-resonance excitation to the integral defined in Eq. (2). Burkert and Li [9] parameterised the experimental Q^2-evolution of the main nucleon resonances ($P_{33}(1232)$, $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$, $F_{15}(1680)$), and assumed single-quark transitions to evaluate the contributions from other resonances. Aznauryan [10] described the resonance excitation in the approximation of infinitely narrow resonances, and included a contribution from one-pion exchange in the near-threshold region. Both models predict a sudden decline in I^{res}_{GDH} as Q^2 falls below 1.5 GeV^2, due to a large negative contribution at low Q^2 by the helicity structure of the P_{33}-resonance. At higher Q^2 the P_{33}-resonance magnetic form factor strongly decreases with increasing Q^2, and the positive contribution to I^{res}_{GDH} arising from the excitation of higher-mass resonances becomes dominant. Neither of these models includes the nonresonant multihadron production channels, which should provide an additional positive contribution for the region $W^2 \leqslant 4.2\ \text{GeV}^2$. Comparison with the data suggests that for $Q^2 \simeq 1.5\ \text{GeV}^2$, the resonance excitation models are not sufficient to fully explain the experimental result for I^{res}_{GDH}. Other predictions exist for the resonance-excitation contribution to generalised GDH integrals, but they are limited to regions of lower Q^2 [26].

To complete the evaluation of the full integral I_{GDH}, data from the DIS region ($4.2\ \text{GeV}^2 < W^2 < 45\ \text{GeV}^2$) were reanalysed in the same Q^2-bins as for the kinematically more restricted resonance region, following the procedure described in a previous HERMES publication [13]. A total of 1.52 million events were selected in this W^2-range. The systematic uncertainty for this region is the same as published in [13,18]. The systematic uncertainty on A_2 in DIS region does not contribute significantly.

In Table 1 the resonance-region contribution I^{res}_{GDH}, the integrals I^{meas}_{GDH} in the full measured region and the full GDH integrals are reported. The latter was calculated in each Q^2-interval by adding to I^{meas}_{GDH} an estimate of the unmeasured contribution for $W^2 > 45\ \text{GeV}^2$. This was calculated using a multiple-reggeon exchange parameterisation [3] for $\sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)$ at high energy, and amounted to about 3.5 μb for all Q^2-bins. A parameterisation for g_1 [27] based on a NLO-QCD analysis provided within 5% the same results as the multiple-reggeon exchange analysis. This difference was taken as the systematic uncertainty of the high-energy contribution. It is worth noting that for the low Q^2-bins, both the statistical and the systematic uncertainties of I_{GDH} are dominated by those from the resonance region. In this region, these uncertainties are large due to the smallness of D and to the large size of η, respectively.

In Fig. 3a the total GDH integral is shown together with the partial integrals for $W^2 < 4.2\ \text{GeV}^2$ and for $W^2 < 45\ \text{GeV}^2$. The contribution of the resonance region to the full GDH integral is small for Q^2 values above 3 GeV^2.

Fig. 3a also shows a prediction [8] based on a Q^2-evolution of the two polarised structure functions g_1 and g_2, without consideration of any explicit nucleon-resonance contribution. This prediction is in good agreement with the experimental data.

In the whole energy range, I_{GDH} is consistent within the uncertainties ($\chi^2/N_{\text{df}} = 0.4$) with a simple $1/Q^2$ power law. This is demonstrated in Fig. 3b where the results for I_{GDH} are multiplied by $Q^2/(16\pi^2\alpha)$. In the deep inelastic limit, this quantity is equivalent to Γ_1 (see Eq. (5)). The present results are in agreement with the measurements of $\Gamma_1 = 0.120 \pm 0.016$ at $Q^2 = 10\ \text{GeV}^2$ [28] and $\Gamma_1 = 0.129 \pm 0.010$ at $Q^2 = 5\ \text{GeV}^2$ [25]. In addition, values of Γ_1 extracted from the present data are also consistent with a measurement of $\Gamma_1 = 0.104 \pm 0.017$ at $Q^2 = 1.2\ \text{GeV}^2$ [25] in which the structure function g_1 was measured in the resonance region.

In summary, the Q^2-dependence of the generalised Gerasimov–Drell–Hearn integral for the proton was determined for the first time in both the resonance and the deep inelastic regions, covering the Q^2-range from 1.2 to 12 GeV^2. In the resonance region, the data suggest that for $Q^2 \geqslant 1.5\ \text{GeV}^2$, existing resonance-excitation models are not sufficient to fully explain the experimental result for $I^{\text{res}}_{\text{GDH}}$. Above $Q^2 = 3\ \text{GeV}^2$ the DIS contribution to the generalised GDH integral is dominant. The Q^2-behaviour of I_{GDH} suggests that there are no large effects from either resonances or nonleading twist, and indicates that the sign change of I_{GDH} to meet the real photon limit occurs at Q^2 lower than 1.2 GeV^2.

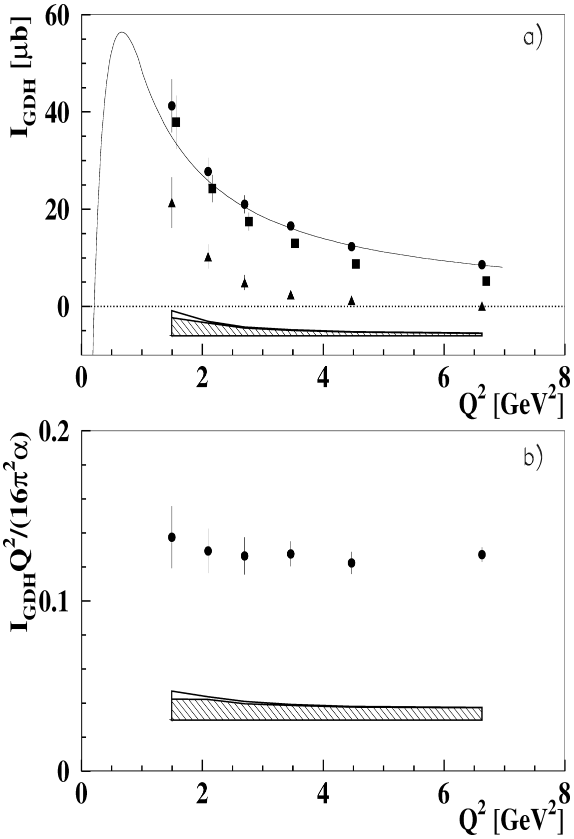

Fig. 3. (a) I_{GDH} as a function of Q^2 for various upper limits of integration: $W^2 \leqslant 4.2\ \text{GeV}^2$ (triangles), $W^2 \leqslant 45\ \text{GeV}^2$ (squares), and the total integral I_{GDH} (circles). The squares have been slightly shifted to make them more visible. The curve is the Soffer–Teryaev model [8] for the total integral. (b) $I_{\text{GDH}} Q^2/(16\pi^2\alpha)$ as a function of Q^2. For both panels, the error bars show the statistical uncertainties, and the white and the hatched bands at the bottom represent the systematic uncertainties for the total integral with and without the A_2 contribution.

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